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The third, and final, area covered in this report is the observation of strong oscillations in Si MOSFET's in the same temperature range as the GaAs effect. The gate voltage required for a minimum did not shift with substrate bias, indicating that the effect was occuring in the accumulated regions on the source and drain. At present the origin of the oscillations is not clear, but we can eliminate the interface as this will not be relevant for GaAs.

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Low Temperatures

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1. Spin dependent recombination at the Si-SiO_2 interface

1a Introduction

There is considerable interest in applying electron spin resonance to a study of charged defects at the Si-SiO_2 interface.[1,2,3] Such a technique may assist in determining the chemical nature of interface states and oxide charge, conventional techniques such as the C-V relation can only determine the net electrical charge at the interface.

The work described here was performed in collaboration with Dr. D. Kaplan at the Cavendish Laboratory and the results presented are based on the first preliminary analysis of the data. A more detailed analysis is being performed and will be described in detail in a later report. The technique used was spin dependent recombination at the Si-SiO_2 interface, and the background to this work lies in the theoretical work of Kaplan, Solomon and Mott[4] and the experimental work of Solomon.[5] In the theoretical work it was shown that a certain degree of recombination proceeds via a trapped electron and a trapped hole. Such a process can only occur if the carriers are in a singlet state. Consequently the result is an increase in the triplet population above the equilibrium value of 3/4. At the e.s.r. condition the spin population is randomised and the ratio of triplet to singlet states is reduced to 3:1, as a result recombination is enhanced.

On the experimental side, Solomon showed that an increase in the forward current of a bulk p-n junction occurred at the e.s.r. condition provided that the current was recombination limited. It was not possible for Solomon to determine if the e.s.r. centres were located at the surface or in the bulk.

Accordingly, this work was undertaken in the hope that, by the use of gate controlled diodes, a distinction could be drawn between surface and bulk centres. The advantage over conventional e.s.r. is that device structures can be used, the disadvantage is that only states at the interface contributing to recombination can be investigated.

1b Experimental

It has been known for some time that the gate controlled diode enables a distinction to be made between suface and bulk generation and recombination centres.[6] Both generation and recombination increase as the Si surface is depleted, reach a maximum and then start to decrease when the surface is inverted, and the Fermi energy at the surface is no longer near mid-gap, Figure 1.

The experiments were performed using gate controlled p^+n junctions with a central p^+ diffusion and an annular aluminium gate. Measurements were at room temperature with a conventional electro-magnet and field modulation applied by a small coil situated just outside the microwave cavity. Precautions were taken with the wiring configuration on the chip in order to minimise the microwave induced voltage across the p-n junction. The forward voltage was less than 0.3 volts, ensuring the current was recombination limited. The spin signal could not be observed on a (100) surface where a post-oxidation high temperature anneal was provided, followed by an aluminium sinter. However, a signal was obtained when these structures were irradiated by 25 keV electrons. This signal was well defined and varied with the diode current, showing a maximum just prior to surface inversion. After irradiation the inversion voltage had increased by 23 volts, corresponding to a change in interface charge of $+3.5 \cdot 10^{12}$ cm^{-2}. It was not possible to distinguish the separate contributions of interface states and oxide charge. The obtained signal was centred at a g value of 2.005. At high values of positive gate voltage the signal and the recombination current increased again, this corresponded to depletion of the p^+ region. The maximum spin dependent signal was about 5 parts in 10^4, and the experimental resolution was about 1 part in 10^5.

A very broad resonance was also found using MNOS memory transistors on the (100) surface. Here the 18Å oxide layer was chemically grown in HNO_3, the interface state density was $\sim 10^{12}$ cm^{-2} as an aluminium sinter was not given. The signal was too broad to allow a quantitative analysis.

1c Conclusion

The absence of an observable signal at well prepared (100) interfaces is also found in conventional e.s.r.[2] The g value of 2.005 is close to the averaged value of the P_b centre which has been found at the (100) interface[1,2] and has been correlated with the mid-gap interface states. These states are those principally responsible for generation and recombination. In view of their removal by hydrogen it is very possible that the centres are trivalent Si i.e. dangling Si bonds.

There is an important difference between the e.s.r. observed in this experiment and conventional spin resonance. The latter case is caused by the presence of an unpaired electron. However, in the recombination experiment, the resonance occurs after the dangling bond has captured an electron. This cannot occur in a straightforward way as there is clearly not an unpaired electron. The captured electron must be shared among several dangling bonds or the centre is more complex. Similar reasoning applies to the case of hole trapping; it is to be noted that the experiment cannot distinguish between hole and electron resonance, although the obtained g value indicates that electron resonance is being measured.

If the trapped carriers are shared between several dangling bonds this does not imply that the density of mid-gap states is correspondingly high. The presence of a captured electron will raise the energy level of another captured electron by a large amount, and so dangling bonds closely separated may only contribute one state to the overall density of states. The distance between the trapped hole and electron must be greater than at least 20Å otherwise the singlet and triplet states will not be degenerate. The maximum distance is about 60Å before tunnelling becomes too difficult. This implies a spin concentration of about 10^{12} cm^{-2}, as the surface area of the junction is about 10^{-4} cm^{-2} a total of $\sim 10^8$ spins was detected.

2. Conductance oscillations in GaAs FET's.

2a Introduction

Previous work has demonstrated that the GaAs Schottky-gate field-effect transistor is a useful system for investigating conduction in an impurity band. The conventional system consists of an n-type film of GaAs 1000-2000 Å thick, epitaxially grown on a nominally undoped 'buffer' layer on a high resistivity (compensated) substrate. A Schottky barrier (aluminium) is formed on the n-type layer and, by applying a voltage to the aluminium gate, the depth of the depletion region is altered and the thickness of the conducting channel varied. At low temperatures transport occurs within the impurity band, which, depending on the doping, may have merged with the conduction band. Previous work indicated that transport becomes two-dimensional when the thickness of the conducting channel decreases to about twice the mean donor separation. The experiments reported here were performed mainly with structures slightly different from those used earlier. The structure is shown in figure 2; an n-type epitaxial layer (8×10^{16} sulphur donors/cm^3) was grown on a p-type substrate ($N_a \sim 10^{18}$ cm^{-3}) and the Al Schottky gate was formed on the n-layer in the normal way. Because of the depletion region at the p-n junction, the conducting channel is forced well away from the metallurgical interface, and its associated disorder, about 1300 Å into the n-region in the absence of a substrate voltage. The potential distribution in the device is also illustrated in figure 1. By varying the gate voltage and the substrate voltage, the location of the conducting channel can be altered. The gate is diamond-shaped, of width 2 μm and aspect ratio ∿300; the distance between the ohmic source and drain contacts is 8 μm.

2b Experimental

Measurements of the DC conductance between 77 and 4.2 K confirmed the existence of a transition from metallic to activated conduction as the thickness of the conducting channel and the carrier concentration decreased. The value of the minimum metallic conductance was close to $0.1e^2/\hbar$ (3×10^{-5} Ω^{-1}) and did not vary as the location of the conducting channel was altered. Above ∿8K, the conductance decreased rapidly but smoothly with decreasing carrier concentration. However, below this temperature and at carrier concentrations below 1.5×10^{11} cm^{-2}, a series of oscillations became apparent; each minimum in the conductance had a width of the order of 5×10^9 electrons cm^{-2}. An example of this effect is shown in figure 3. A classical treatment of the depletion layer gives the width of the conducting channel increasing up to 100 Å for 10^{11} electrons cm^{-2}. As the current increased rapidly with increasing crrier concentration, a linear scale is used with the scale progressively changed by a factor of 10. Although the depth of the depletion region confining the conducting channel varies as $(V_g + \phi)^{1/2}$ where V_g is the gate voltage and ϕ the barrier height, for the small changes in V_g shown here, the width of the conducting channel and the carrier concentration both vary linearly with V_g. The scaling factors are shown in the figure captions.

The conductance in the region of the oscillations was well below σ_{min} and, as therefore expected, was thermally activated. The oscillations grew in intensity with decreasing temperature below 4.2 K as shown in figure 4. It is not clear whether the conductance shows a simple activation energy, but the activation energy in the maxima was of the order of 0.5 meV and in the minima, 1.0 meV. It was also found that weaker oscillations appeared with decreasing temperature. The basic effect itself was not dependent on the location of the channel, although near the metallurgical interface the conductance for a particular concentration did vary slightly with channel location.

The effect was also found in conventional devices, where an n-layer (8×10^{16} donors cm^{-3}) was grown on an undoped buffer. However, some conventional devices with this doping failed to show the oscillations. It was not clear whether this was related to the quality of the buffer layer. Work on a conventional device with a doping of 2.3×10^{16}donors/cm^3 revealed weaker oscillations.

The periodicity of the structure was examined and it was found that the location of the strongest minima (virtually all those apparent at 4.2 K) fitted a simple series in terms of mean electron separation r_{ee}, given by $r_{ee} = (4/\pi n)^{\frac{1}{2}}$ where n is the electron concentration. The minima were found when r = Nx, with N integral, and, for a doping of 8×10^{16} cm-3, x was observed to be between 90 and 114 Å, depending on the sample or on the location of the conducting channel in the n-p structure. N had values 3,4,5, 6,7,8 and occasionally 9. One conventional device showed a main series with N taking values 5,6,7,8,9,10 and 11. Weaker minima were present, which often grew rapidly with temperature below 4.2 K and these appeared when r_{ee} took half-integer values between 2.5 and 7.5. Occasionally some of the minima were absent. In addition a weaker structure was noticed, not characterised by a conductance minimum but by a sudden change in gradient of the plot of conductance against gate voltage. These 'shoulders' often became minima at lower temperatures; they were not found in the conventional devices but only in the n-p structures. They tended to be more pronounced at the higher carrier concentrations and appeared between the integer and half-integer series. It was found that they fitted the above formula with values N + 1/4 and N + 3/4 instead of integers, although it should be stressed that, for the small changes in carrier concentration between these series, errors are becoming significant. Table 1 shows these various series for the n-p structure with a substrate voltage of 0.3 V. This was the most complete set of data obtained from the experiments.

The effect of the source-drain field on this series is complex and as yet not fully clear. In general it required variation of both the temperature and the source-drain field for identification of all the half and quarter series. Assuming that the integer series holds for the weak oscillations observed in the sample with 2.3×10^{16} donors cm^{-3}, a periodicity of 225 Å was obtained. There is thus a clear difference between this value and the values between 90 and 114 Å obtained for the samples with doping of 8×10^{16} cm^{-3}, both for conventional and n-p structures.

As in the inversion layer, the determination of the carrier concentration is not unambiguous. It was found that the lowest measurable sheet conductance at 4.2 K was $\sim 10^{-12}\ \Omega^{-1}$, which is very close to that at 77 K cut-off. Accordingly the corresponding value of the gate voltage was taken to denote zero carrier concentration. With increasing substrate voltage a small p-n junction leakage current flowed, which prevented current measurements at the lowest values of the carrier concentration. When this problem was encountered the results were examined to determine whether they followed a law of the form $n' + n_o \propto 1/N^2$, where N takes the integer values, n' is the carrier concentration corresponding to a strong minimum and is measured from the lowest detectable device current and n_o is the undetectable carrier concentration. The results gave an excellent fit to this law for the same values of N as when r_{ee} was ascertained directly. The values of n_o obtained were of the order of 10^{10} cm^{-2}, a correction sufficiently small for the estimate of r_{ee} derived from n' to be linear with N for all except the higher integer values.

The effect of the source-drain field on the oscillations was complex. Ohmic behaviour was found to ∿4 V cm^{-1}, although fine structure in the minima was erased by fields near this value, Figure 5 shows the fine structure observed at low fields. For fields above ∿4 V cm^{-1} the main series of oscillations was dampened and slightly shifted in position, but the half-integer series was enhanced. An example of this is shown in figure 6. The greater resolution of the minimum at N = 5.5 is due to a decrease in current with increasing source-drain field, an interesting example of a differential negative resistance. Fields greater than ∿12 V cm^{-1} completely erased all the structure, both for the integer, half-integer and the quarter-integer series and a strong non-ohmicity was found. The sample doped with 2.3 x 10^{16} donors/cm^3 showed strong non-ohm. behaviour at lower fields and the oscillations were erased at 0.5 cm^{-1}.

Application of a magnetic field of 80 KG at 4.2 K resulted in a very slight enhancement of the structure; this was found for fields both parallel and perpendicular to the conducting sheet.

2c Conclusion

Turning now to possible origins of the oscillatory effect, qualitatively it appears as if the Fermi energy E_F is progressively passing through minima and gaps. Minima might arise if there were many types of shallow donor. However, E_F must rise at least 3 meV through the region of the oscillations in order for each oscillation to be observable when kT is ∿0.5 meV. Such a difference in the ionisation energy of shallow donors is unknown in GaAs and in addition the donor overlap would have to be very small to retain the structure.

There are detailed treatments of the effects of quantisation perpendicular to the channel arising in similar structures and, in a similar manner to inversion layers, sub-band energies have been calculated in a self-consistent way. In a sense the system contrasts with the inversion layer in that increasing the carrier concentration widens the conductivity channel, weakens the potential well and decreases the energy splitting. Thus if sub-bands pass progressively through E_F an effect on the conductance may be observed. However, the oscillations are observed when the quantisation is very strong, that is with carrier concentrations less than 10^{11} cm^{-2} and with energy splitting ∿10 meV. Hence E_F should lie in impurity levels derived from the ground state. Even if E_F passed into higher sub-bands, it is not clear why the conductance should show a strong decrease and why the intermediate structure appears with decreasing temperature.

Finally, we consider the role of many-body effects, as suggested by the minima with mean electron separation. Straightforward Anderson localisation would be expected for this system. Classically the number of electrons within the sheet is equal to the number of donors. However, because of the shape of the enclosing potential well and the quantisation of the conduction band, the classical approximation for the depletion layer is not justified and the volume of the channel contains more donors than electrons. Ionised donors further away give rise to potential wells and hence, available sites within the channel. If only the donors within the channel are considered, the mean distance between sites (∿200Å) is twice the Bohr orbit (98Å). Taking into account sites due to donors some distance away, the mean distance is then nearer than the dimension of the Bohr orbit. The net result should be a smoothed-out potential and hence a large localisation length. This may allow a greater degree of electron ordering than is normal in a random array of donors, giving rise to a Coulomb gap and a consequent effect on the activation energy for conduction in the manner discussed by Mott and Pollak and Knotek. Minima in the conductance occur when electron ordering is greatest. For a regular array of donors, this situation could arise when the electron lattice is commensurate with the host lattice and so when the mean distance between electrons is a multiple of the mean distance between sites. The situation is difficult to envisage if the donors are distributed randomly and there is little significance to the mean separation between sites. In order to explain the value of x of about 100 Å, it is necessary to assume that donors some 500 Å from the conducting channel give rise to available sites and this occurs for donors some 1000 Å from the channel in the conventional device. It this is so, then as most sites originate from donors some way from the channel, two-thirds of the sites represent potential fluctuations of less than ∿3.5 meV, which gives a fairly smooth potential with fluctuations of the order of the Coulomb gap. According to Pollak and Knotek the Coulomb gap is $\sim 2E_C(E_C/W)^{\frac{1}{2}}$, where E_C is $e^2/r_{ee}\varepsilon$, ε is the dielectric constant and W the random energy. Clearer insight into the effect of the Coulomb interaction would be obtained if the one-electron density of states was known in greater detail, and any theory would have to take into consideration the added randomness of compensating centres which may be present at a low level.

It is possible that the value of x is not related to the site separation, but rather arises from vibrational properties of the interacting electrons. On the other hand, the increase in periodicity to 225 Å for the sample with 2.3×10^{16} donors cm^{-3} is consistent with the site separation varying inversely as the square root of the doping. The enhancement of the half-integer series by an increased electric field may, if ordering is occuring, be envisaged as arising from an enhanced ordering of the electrons when the electron lattice is not commensurate with the host lattice.

The weaker oscillations found for the device with $N_D = 2.3 \times 10^{16}$ cm^{-3} may be due to the enhanced effect of the impurity potential. This value of doping is below the critical concentration for the Anderson transition in the impurity band. This may result in stronger localisation with less scope for any possible ordering.

A small piece of evidence pointing to a many-body effect as the origin of the oscillations is the retention of the periodicity for different locations of the channel. The conductance was found to vary slightly, for a constant carrier concentration, as the channel (in the n-p structure) was pushed to the metallurgical interface. Thus, the oscillations appeared at certain values of carrier concentration which were independent of the density of states in the impurity band.

It must be stressed that the principal periodicity is obtained by considering the strongest oscillations, those which persist at the higher temperatures, and if the entire range appearing at the lowest temperatures is considered, the effect is more periodic in the carrier concentration itself.

This is particularly in evidence when accompanied by the shifts in position caused by increasing the source-drain field.

We will shortly be examining the doping dependence of the oscillations hopefully this will help in determining the origin of the effect.

3. Conductance oscillations in silicon MOSFETs

3a Introduction

In this section we report on conductance oscillations in (two dimensional) accumulation layers on doped silicon, both for n and p type material. As will be shown the doped layers are the source and drain regions of Si MOSFETs.

3b Experimental

Figure 7 is an example of such oscillations found at 4.2 K with a p channel MOSFET, the results are shown for differing values of substrate bias. The effect of applying the bias is to alter the threshold voltage, V_T, and hence the carrier concentration which is proportional to $(V_G - V_T)$. Figure 7 shows that the location of the minima is not a function of the bias, nor is the value of conductance in the strongest minima, but outside this region the conductance does decrease with decreasing carrier concentration. These results imply that the current limiting mechanism is in the surface of the doped regions near the junction with the inversion layer. These regions are accumulated and, due to the increase in barrier height with distance from the interface, determine the current flow into the inversion layer. For concentrations much less than 3×10^{18} cm^{-3}, the doped regions are frozen out at low temperatures. Figure 7 indicates that the accumulation layers are responsible for the conductanc minima and, for this regime of gate voltage, the inversion layer acts as a resistance in series with the accumulation layers.

We have studied the oscillations using both p and n channel devices, with a substrate material of ∿10 Ωcm resistivity. Qualitatively the strongest effects are found when heat treatments are used which produce a long doping profile in the source and drain regions i.e. an appreciable sideways diffusion of the dopant. Thus, the strongest effects were found when, after oxidation at 1000°C, a 12 hour inert gas anneal at 950°C was performed. The oscillations are weak, or absent, when the source and drain regions are sharply defined. This dependence upon the device fabrication conditions is also accompanied by a dependence on the applied source to drain voltage. Using devices with 250 μm source-drain separation, we have found that the strongest oscillations persist up to an applied voltage of 20 mV. Whereas, when the source and drain regions are well defined, the oscillations, if present, disappear when the source-drain voltage is greater than ∿50 μV.

As stated, the strongest effects were obtained using devices which, at low temperatures, were obviously injection limited, i.e., very low "mobility" with the conductance-gate voltage relation largely independent of substrate bias. Nevertheless, due to the extremely non-ohmic behaviour of the oscillations they could be observed at fields of 10^{-3} volts cm^{-1} with devices which, at higher fields, showed normal inversion layer behaviour.

Drifting Na^+ ions to the Si-SiO_2 interface altered, in the expected way, the gate voltage at which the minima appeared and also decreased the magnitude of the oscillations. However, for n channel devices, when 4×10^{12} Na^+ ions cm^{-2} were present, new and more subtle oscillations were introduced, this is illustrated in figure 8.

The analysis of the oscillations was not as straightforward as in the GaAs work. Here there was considerably more structure and a simple relation was not immediately apparent. It was often found that the minima appeared periodic in carrier concentration n, with a whole spectrum of periodicities. However, there is evidence, limited at present, that the dominant oscillations may be periodic in inter-carrier separation.

A principal difference between this work and the GaAs situation is that here we are increasing the carrier concentration from a starting point of one per impurity. In addition we do not know the relevant impurity concentration, and the effect may be occurring in a region where there is a doping profile, possibly increasing the number of oscillations. Typically the oscillations are observed when n is increased up to $\sim 4 \times 10^{11}$ carriers cm^{-2}. As the basic effect is occurring in a region of heavy doping, it is possible that the oscillations occur when the decrease in carrier separation is a fraction of the impurity separation. The Si-SiO_2 interface may present a slight complication, we have found that sometimes different diffused regions exhibit the oscillations at slightly different values of gate voltage, although the periodicity is largely unaffected.

Fine structure in the conductance-gate voltage relation can be present either with or without the oscillations. This consists of sharp spikes, which increase in size as the temperature decreases, and can be a factor of 5 greater than the mean value of conductance. The width of each spike is $\sim 10^9$ carriers cm^{-2}. They are erased by a very low value of field, ~ 0.02 volts/cm, and appear to originate from the source and drain regions. The fine structure is, in the case of an MNOS device, erased by repulsive charge although not attractive charge. This structure appears to be a more developed form of the fine structure in the differential of conductance (field effect mobility), which is likewise associated with the source and drain regions and is also dependent on the interfacial charge.[14] The oscillations disappeared when the temperature was greater than about 15K.

3c Conclusion

The observation of the oscillations in both n and p type Si clarifies the situation, in that explanations peculiar to the GaAs device are removed. Similarly, explanations for the effect in Si based on the role of the Si-SiO_2 interface are difficult to sustain in view of the GaAs results. At present it seems that the most plausible explanations are a periodic instability of the electrons arising from a many body effect, leading to oscillatory phenomena about a fundamental length scale, or just possibly an effect arising from the narrowing of the conducting channel, or sharply localized states arising from defects or dislocations.

Finally, it is to be stressed that these results on substrate bias and source-drain limited conduction are not relevant to experiments reported previously. The conclusions reached in the earlier work on the nature of interfacial charge, and the effects of substrate bias, are unaffected by these new findings.[15,16] A particular disadvantage of the devices used for the experiments reported here is that the doping is unknown in the region where the effect is occurring. This will be remedied in the future work where the effect will be sought in accumulation layers formed on highly doped substrate material.

Figure Captions

1. Schematic illustration of the recombination current as a function of gate voltage, the peak due to surface recombination is indicated.

2. (a) The p-n structure used in this work, G and D are ohmic contacts to the n-type epitaxial layer. (b) Schematic illustration of the potential well in the n-region of the system and the Fermi energy, E_F. The line marked as such represents the impurity band which is occupied up to E_F.

3. The relation between conductance and gate voltage at 4.0 K obtained with a substrate voltage of -0.2 V. The method of plotting conductance was adopted because of the increase of nearly four orders of magnitude over the range of V_g. For the displayed change of V_g, the carrier concentration increases linearly at a rate of 5.95 x 10^{11} electrons cm^{-2} V^{-1}. Minima A,B,C,E and G fitted the main series for integer values of 9,8,7,6 and 5 respectively and a mean periodicity of 90 Å. D, which was not observable at 4.2 K, F and H belonged to the half-integer series with values 6.5, 5.5 and 4.5 respectively. The broken curve shows the strengthening of G and H at 1.8 K, where, for clarity, the conductance is multiplied by a factor of 5. y gives the scale of the conductance. There is a quarter-series 'shoulder' between C and D; the development of this 'shoulder' to a minimum at lower temperatures is clearly shown in Figure 4. The arrow denotes the conductance zero which is taken as the zero of carrier concentration. The applied field is 2.5 V cm^{-1}.

4. The temperature dependence of the oscillations shown in Figure 3. A significant feature is the evolution of the quarter series shoulder between C and D into a minimum.

5. The structure observable in the minima at a low source-drain field of 0.8 V cm^{-1}. The oscillations were obtained on a p-n structure with -0.4 V applied to the substrate. For the values of gate voltage illustrated, the carrier concentration varied linearly with V at a rate of 6.74 x 10^{11} carries/V.cm^2. When the source-drain field was increased to 2.5 V cm^{-1}, E' and D' were erased, resulting in a single minimum in each case; F' was strengthened and fitted on the half-integer series at 4.5. A is also strengthened by an increased field and fits on the half-integer series at 9.5, B, C, D, E and F fit on the main series with values 8,7,6,5 and 4 and a periodicity of 95 Å. The minimum with integer value 9 is not clear on this plot, but at 2.5 V cm^{-1} B is weakened and this then becomes apparent. The small current at the lowest gate voltage contains a component due to p-n junction leakage; the zero of carrier concentration obtained from a $1/N^2$ plot is close to 0.22 V.

6. The differential negative resistance caused by a stronger source-drain field which enhances the half-integer splitting as well as damping the main series. The carrier concentration increases with gate voltage at a rate of 5 x $10^{11}cm^{-2}$ V^{-1} and the periodicity of the main series is

114 Å. The temperature of measurement is 4.2 K. It must be pointed out that whereas the enhanced field always strengthens the half-integer series, the differential negative resistance is not found at other half-integer values, - - - 4 V cm^{-1}, ——— 2.5 V cm^{-1}. The insert on the figure illustrates the difference between integer, half-integer and quarter-integer series at 4.2 K.

7. The effect of substrate bias on the current-gate voltage characteristic of an n channel MOSFET at 4.2 K: a) = +1.0 volts, b) = +0.5 volts, c) = 0 and d) = -1.0 volts. The location of the minima are unaffected by the bias whereas the current is. The device dimensions were 400 μ x 250 μ and the source-drain voltage was 1 mV.

8. The weak structure produced by 4 x 10^{12} Na^+ ions cm^{-2} at the Si-SiO_2 interface of an n channel device. The device was circular geometry, source-drain separation 18 μ and aspect ratio 20:1. The continuous line was obtained with 100 μV applied voltage and the dashed line with 1 mV.

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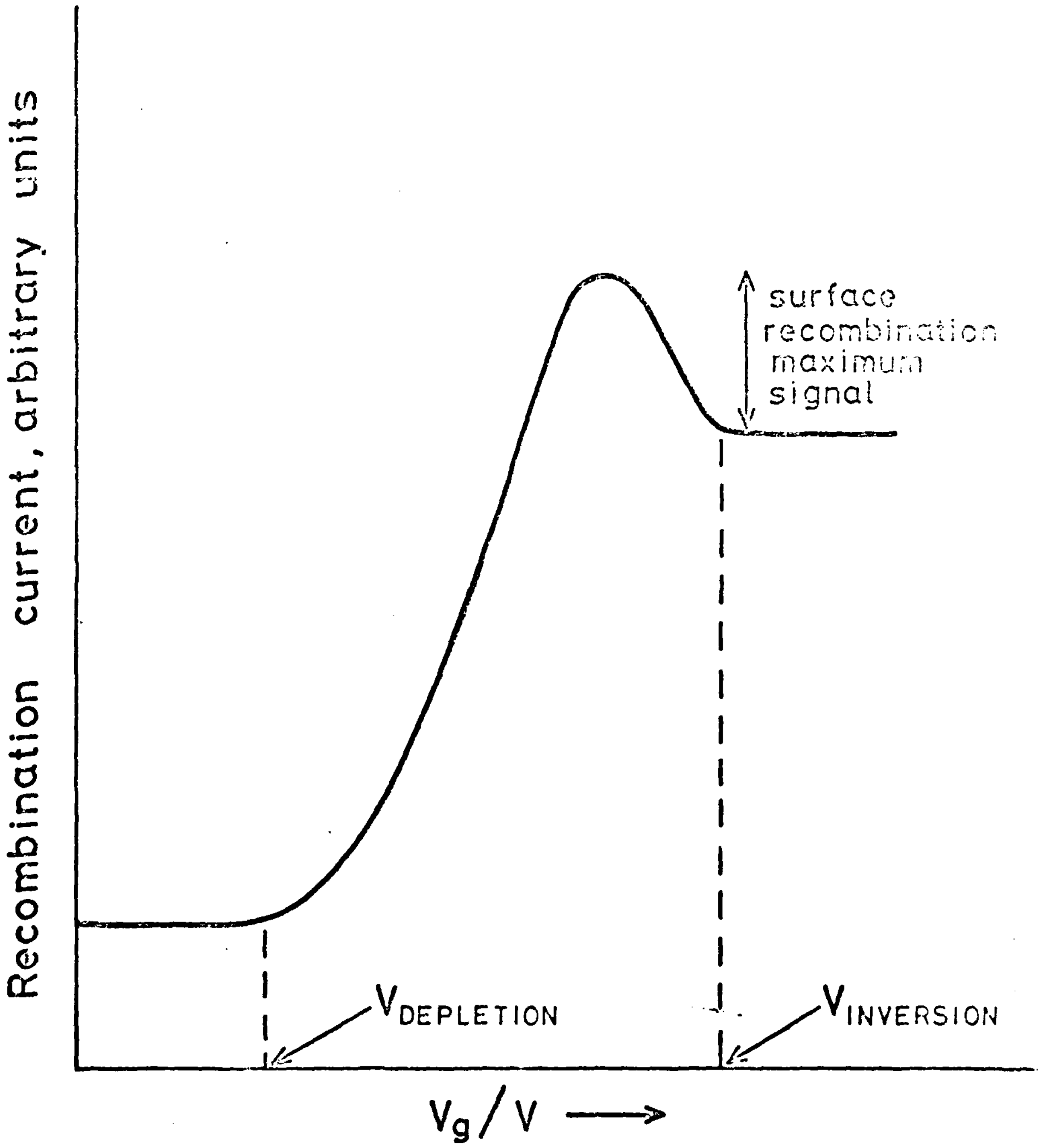
Recombination current, arbitrary units
surface
recombination
maximum
signal
$V_{DEPLETION}$
$V_{INVERSION}$
V_g / V →

FIGURE 1

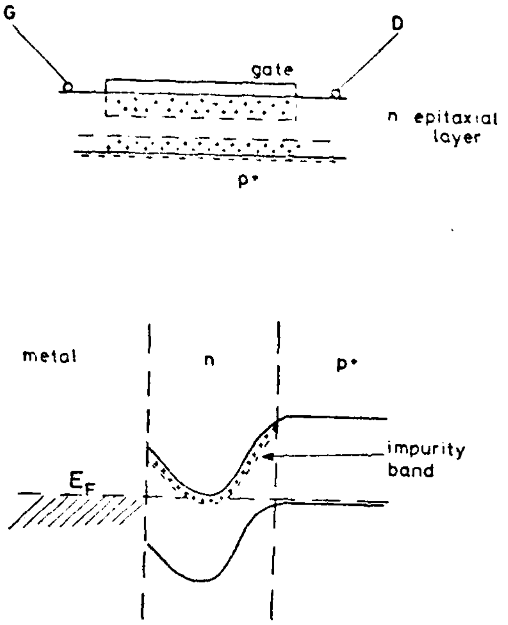
G
D
gate
n epitaxial layer
p+
metal
n
p+
impurity band
E_F

FIGURE 2

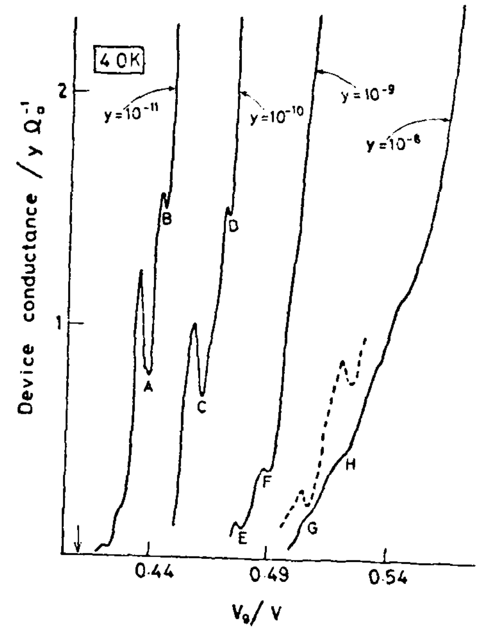

FIGURE 3

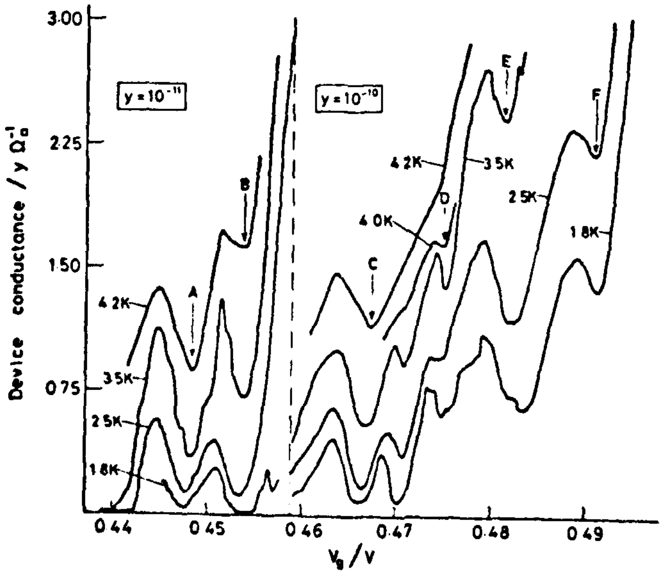

FIGURE 4

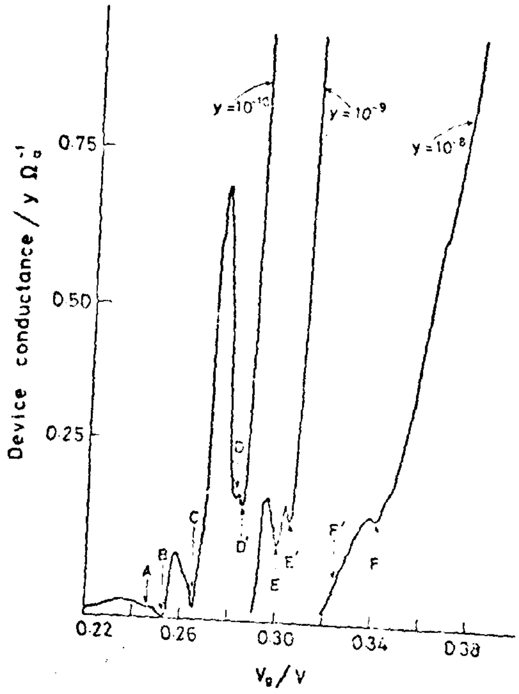

FIGURE 5

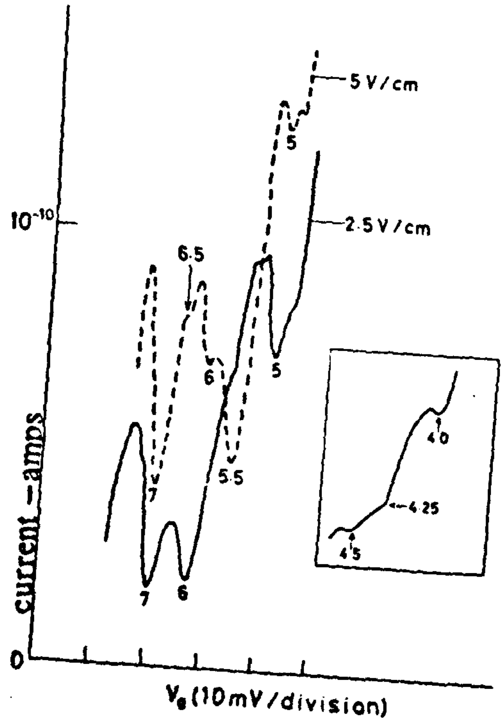

FIGURE 6

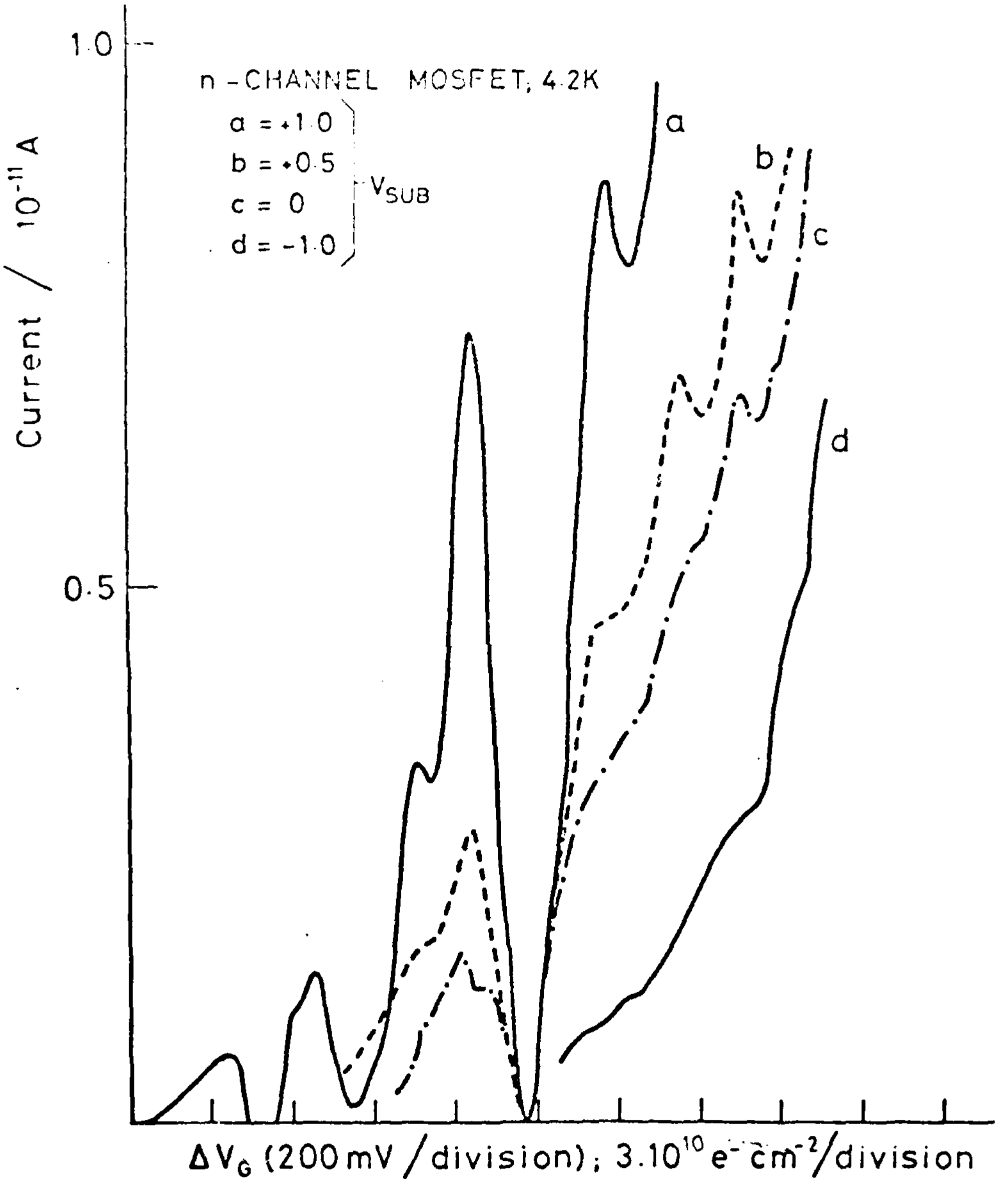
1.0
0.5
Current / 10^{-11} A
n-CHANNEL MOSFET, 4.2K
a = +1.0
b = +0.5
c = 0
d = -1.0
V_{SUB}
a
b
c
d
ΔV_G (200 mV / division); 3.10^{10} e⁻ cm⁻² / division

FIGURE 7

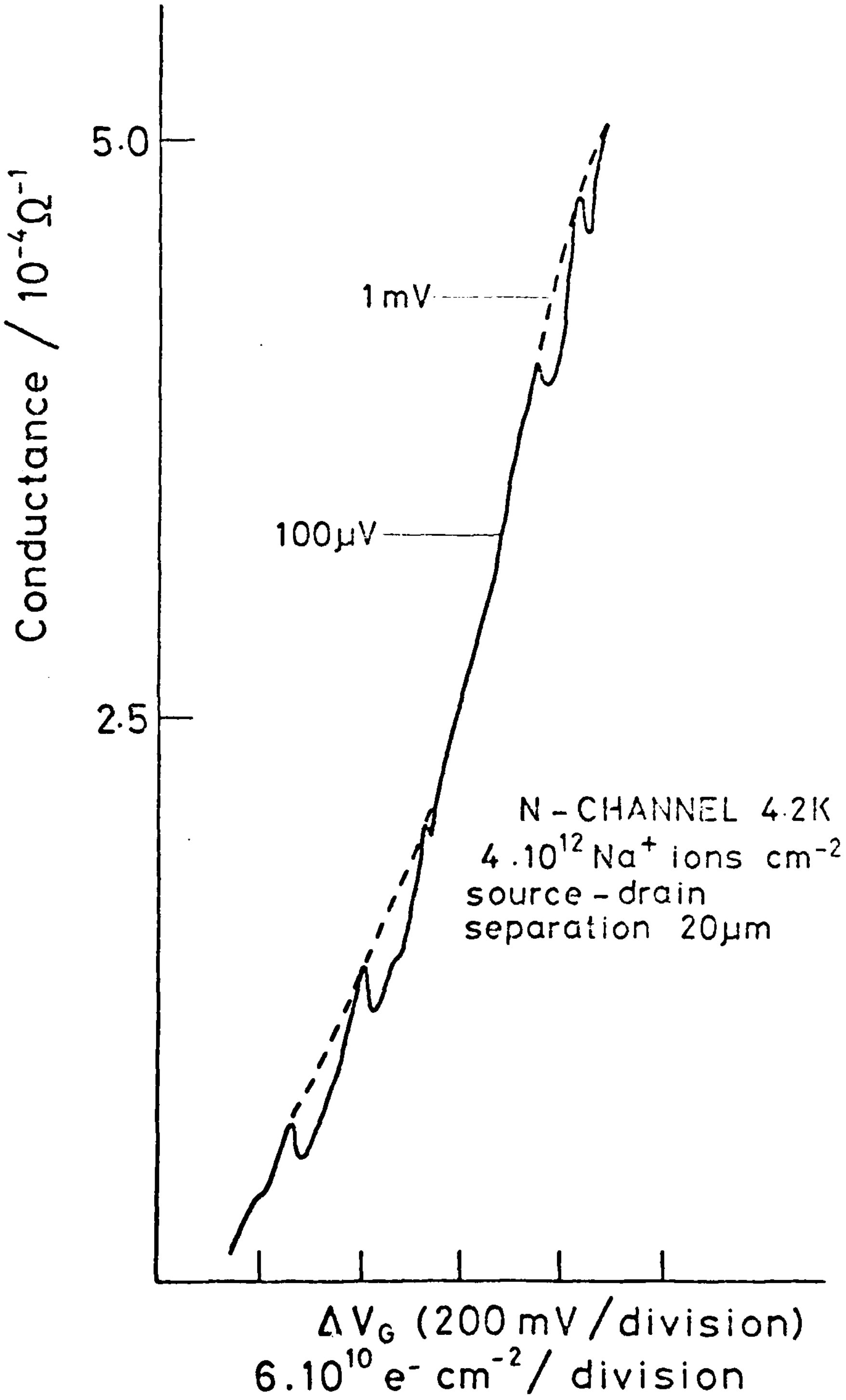
5.0
2.5
Conductance / $10^{-4}\Omega^{-1}$
1 mV
100µV
N - CHANNEL 4.2K
$4 . 10^{12}$ Na$^+$ ions cm^{-2}
source - drain
separation 20µm
ΔV$_G$ (200 mV / division)
$6 . 10^{10}$ e$^-$ cm^{-2} / division

FIGURE 8